

# Two Be stars in the Small Magellanic Cloud with B[e]-like properties

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## ABSTRACT

We present an analysis of UVES and MIKE (ground based) high resolution and *Far Ultraviolet Spectroscopic Explorer* spectra of two novel and photometrically variable bright blue stars in the SMC; OGLE004336.91-732637.7 (SMC-SC3) and the periodically occulted star OGLE004633.76-731204.3 (SMC-SC4). The light curves of these stars exhibit multiple frequencies, and their spectra are similar. The latter are dominated by absorption/emission features produced in a circumstellar (CS) envelope whereas photospheric features are barely visible and forbidden emission lines are not visible. Modeling of spectral features indicates similar physical conditions for the CS envelope in both stars. An optically thick, slowly and thermally stratified disk. SMC-SC4 is noteworthy in showing blue discrete absorption components (“BACs”) in their spectra possibly indicating the shock interaction between high velocity and low velocity material. Optical spectra from two spectra separated by 5 years show little change in the radial velocity over this period. However because these observations happen to be made in roughly similar phases over their long period, these suggest only that the stars are not in close binaries. We interpret the occultations and additional photometric nearly periodic variability in SMC-SC4 as due to covering of the star by a density modulation in a sector of a quasi-Keplerian circumstellar disk. Altogether, we suggest that these stars are prototypes of a larger group of stars, which we dub the “bgBe’s” and discuss their similarities and differences with respect to the well known sgB[e] variables. Although SMC-SC3 appears to be a member the open cluster NGC 242, the evolutionary context of these stars is unclear.

**Key words:** stars: early-type, stars: evolution, stars: mass-loss, stars: B[e] stars: variables-others

## 1 INTRODUCTION

The evolution of massive stars is an important topic of stellar astrophysics, because it provides clues to the mechanisms that feed the Galactic medium with the building blocks of future generations of stars. During their evolution, massive stars having a solar composition lose some large fraction of their mass towards the interstellar medium and may eventually explode as supernovae near the end of their lifetimes. Owing to their weaker winds, the outcomes for metal poor stars are still unsettled but may be quite different. Many of the evolutionary stages of massive stars are short-lived and hence challenge our ability to characterize them in an evolutionary scheme. Detecting objects in these brief phases of evolution should be of great aid to test current theories of massive star evolution, especially if they represent populations with low metal abundances, a condition that is found in the Large and particularly in the Small Magellanic Clouds. Catalogs of Be star candidates, that is, B stars with extraordinary variable light curves in the Magellanic Clouds (e.g., Mennickent et al. 2002, hereafter M02 and Sabogal et al. 2006), provide excellent material for detailed analysis of possible massive pre-main sequence objects and blue stars in rapid evolution stages in these galaxies. A census of the pre-main sequence population of massive stars in the Clouds has not yet compiled and thus is poorly known. In fact, only a few objects have recently been placed in this category (Beaulieu et al. 1996, Lamers et al. 1999, de Wit et al. 2002, de Wit et al. 2003). The general characteristics of these objects are their infrared excesses, usual association with nearby nebulosities, their irregular photometric variability, and, when well enough studied at high spectroscopic resolution, evidence of infalling circumstellar matter. In their study of photometric OGLE light curves of B-type variables in the Small Magellanic Cloud, M02 speculated that some of the quasi-periodic or periodic variables (Type-3 stars) they discovered might be pre-main sequence B stars surrounded by massive gas envelopes.

Alternatively, we note that other objects described in the M02 and Sabogal et al. (2006) catalogues have a number of similarities with the group of B[e] variables, of which only five are currently known in the SMC (Wisniewski et al. 2007; W07). These are B stars with spectra exhibiting hydrogen line emissions,  $(V - K)$  color excesses between 1.2 and 4 magnitudes, and occupy

regions usually well above the main sequence of the H-R Diagram (e.g., Zickgraf et al. 1998, Zickgraf et al. 1996, and W07). Lamers et al. (1998) describe these stars as exhibiting moderate to large infrared excesses, generally irregular light curves, the presence of nonspherical circumstellar (CS) structures, winds, and in their spectra emission lines of permitted Fe II and [Fe II] and [O I]. According to these authors, the B[e] stars are a highly heterogeneous general population, consisting of five subclasses. Two of these subclasses, the “sgB[e]” (supergiant) stars and the “unclassified,” can exhibit long-term variations in their light curves. In particular, “Algol-like variations” in the light curves have been discussed for a few B[e] stars like HD 45677 and UX Ori (de Winter & van den Ancker 1997, Grinin et al. 1994). The variations of these stars are aperiodic and are generally confined to long intervals of a few years. The sgB[e] stars have a particular set of properties that are largely, though not completely, similar to our program objects. For example, the sgB[e] variations *can* have lower luminosities than supergiant B stars and photometric IR excesses indicative of the presence of warm CS dust. As for the more general group of B[e] stars, the sgB[e] stars have spectra that display forbidden lines of [Fe II] and in some cases molecular lines (Heydari-Malayeri 1990, Gummertsbach et al. 1996, Wisziewski et al. 2007).

One of the interesting properties of the high luminosity B[e] stars, that could be relevant for the objects discussed in this paper, is their hybrid wind character, that is, a dual wind structure consisting of a dense slow outflow at the equator and a fast hot one in the polar regions. Pelupessy et al. (2000) and others have argued that this structure results from a combination of the bistability mechanism for a polar component and rotationally induced wind compression for wind efflux emanating from the stellar equatorial regions. Kraus & Lamers (2003) have presented empirical density models for sgB[e] star wind/disk system. Their central argument is that in order to permit the presence of appreciable warm dust and CO and TiO molecules, the equatorial regions must be optically thick and outflowing slow to effectively shield gas and thereby permit formation of multiatomic species. The Kraus & Lamers models exhibit disk-like structures for which loci of constant ionization fan outward from the central plane from distance. This permits the detection of multiple types of species by observers at intermediate aspects to the star-disk system. Depending on the details of the model solution and the ionization level chosen, these contours may or may not touch the stellar surface. In particular, the He I ionization surface seems most assured of touching the surface, but because it opens to the widest angle it would likely contribute the smallest column length to CS line formation.

Knowing that any study of M02 variable stars requires spectroscopic follow-up to fully understand their variability, we selected in year 2001 two Type-3 stars for a high resolution spectro-

scopic analysis with the ESO Ultraviolet-Visual Echelle Spectrograph (UVES). The stars chosen were those in the M02 catalog having visual magnitudes brighter than 14.2. There are 8 stars satisfying this condition among the 78 SMC Type-3 stars so cataloged. We selected this luminosity simply to assure reasonably high S/N in the spectra during the short available observing window we had available with the UVES. The stars were chosen OGLE004336.91-732637.7 ( $\equiv$  SMC-SC3-63371, MACHO ID 213.15560; hereafter SMC-SC3) and OGLE004633.76-731204.3 ( $\equiv$  SMC-SC4-67145, MACHO ID 212.15735.6; hereafter SMC-SC4). Spectra of both objects showed strong CS gas absorptions. This fact motivated us to obtain additional optical and also FUV spectroscopy, leading to the broad-band study described in this paper. SMC-SC3 is a probable member of the open cluster NGC 242 (at a distance of  $\sim 10''$  from the cluster center). M02 reports for this star two periodicities of 118 and 15 days, whereas SMC-SC4 is an emission line object showing occultations (brightness minima) that recur every 184 days or so, with additional nearly periodic photometric variability in time scales of  $\sim 24$  days (Mennickent et al. 2006; hereafter M06).

In this paper we examine whether these two stars are pre-main sequence B-type, classical Be, or B[e] stars. Of these, the above sgB[e] possibility will find the closest match. In Section 2 we give a summary of our observations and present the methods of data reduction and analysis. In Section 3 we present the methods of spectral line analysis and the results of our photometric and spectroscopic analyses in Section 4. Discussion and Conclusions are given in Sections 5 and 6. The goals of this paper are to elucidate the nature of these two rather luminous B-type variables, to discuss their unique array of CS lines, and to pave the way to assign an evolutionary state of a potentially new class of Be stars related to the sgB[e] stars.

## 2 OBSERVATIONS AND DATA REDUCTION

High resolution spectra at resolving power  $\sim 40\,000$  were obtained on 2001 May 17 with the UVES spectrograph in dichroic modes at the UT2 telescope in the ESO Paranal Observatory, Chile. The four CCD chips allowed sampling the spectral ranges of 3050-3870 Å, 4780-5756 Å, 5832-6807 Å and 6704-8517 Å. A slit width of  $1''$  was used, allowing us to obtain good spectra in 600 sec exposures. Wavelength calibrations were performed with the UVES pipeline at the telescope. The *rms* of the wavelength calibration function regarding Th-He-Ar comparison lines was a  $\sim 0.01$  km s $^{-1}$ . The spectra were normalized to the continuum and no flux calibration neither telluric correction were intended. Additional spectra were obtained with the *Magellan Inamori Kyocera Echelle* (MIKE) spectrograph at the Clay telescope in Las Campanas Observatory, Chile

in 2007 November 09. For this double echelle spectrograph the wavelength range was 3390–4965 Å (blue part) and 4974–9407 Å (red part) whereas the slit width was 0.7". The resolving power and dispersion were about 50 000 and 0.02 Å pixel<sup>-1</sup> (for the blue part) and 40 000 and 0.05 Å pixel<sup>-1</sup> (for the red part). The *rms* of the calibration function for these spectra was a  $\sim 0.01$  km s<sup>-1</sup>. The spectra were reduced and calibrated with IRAF. A summary of the observations is given in Table 1.

In addition, far-UV spectra were obtained with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*), as detailed in Table 2. These data cover the continuous wavelength of approximately  $\lambda\lambda 929\text{--}1187$  Å by means of eight independent MAMA detector segments. The spectral resolving power among these varies but is typically 15 000. The spectra were reduced with the CalFUSE version 3.1.8 pipeline system, which was very similar to the last version used for the final reprocessing of the *FUSE* archive.

### 3 METHODOLOGY

Much of the analysis in this paper relies on spectral line synthesis, so we first describe the methods used for this analysis. We have assumed  $\log g = 3.5$ , appropriate for luminosity class I, early B-type stars (Crowther et al. 2006), and a metallicity of  $0.2 \times$  solar for our objects (e.g., Dolphin et al. 2001, Mighell et al. 1998, Dufton et al. 2005). The spectra were analyzed using Hubeny/Lanz SYNSPEC and CIRCUS programs (Hubeny, Lanz, & Jeffery 1994, Hubeny & Heap 1996). For CIRCUS analysis an input temperature for an intervening circumstellar structure,  $T_c$ , and other parameters must be assumed as well. The Fe II and Si II lines below suggest a microturbulence  $\xi$  in the range of 5–10 km s<sup>-1</sup>, and we assume the disk is comoving at a constant velocity. We also posited that the foreground “cloud” (CS wind/disk) covers the star completely in our models. These assumptions require the matching of the computed equivalent widths to the observations using a two-parameter fit in  $T_c$  and column density. It was readily apparent, both from the columns needed to fit the observed line strengths as well as from strength ratios of lines arising from the same ion, that the CS lines are optically thick. In some cases the lines are observed to have peak equivalent widths (EWs) as large as we can compute them even from assumed optimal conditions. This suggests that they are indeed formed in conditions near the optimal  $T_c$  and column density values. However, this assumption does impose errors, generally as underestimates in the column density. Thus, if the temperature other than the optimal value, a larger column density will be required in the line fitting. This dependence emphasizes correlated errors in the determination of

**Table 1.** Summary of UVES/MIKE observations. The MJD numbers at mid exposure are given. The ephemeris for the occultations of SMC-SC4 is 2 450 709.9(2) + 183.9(1.0) E. For SMC-SC3 we use 2 450 000.0 + 119 E.

object	instrument	UT-date	airmass	ccd	grating	exptime (s)	mjd-obs	phase
SMC-SC3	UVES	2001/05/17	1.96	CCID-20	CD#3	600	52411.39285	0.26
SMC-SC3	UVES	2001/05/17	1.96	CCD-44	CD#1	600	52411.39287	0.26
SMC-SC3	UVES	2001/05/17	1.91	CCID-20	CD#3	600	52411.40188	0.26
SMC-SC3	UVES	2001/05/17	1.91	CCD-44	CD#1	600	52411.40189	0.26
SMC-SC4	UVES	2001/05/17	1.86	CCID-20	CD#3	600	52411.41265	0.26
SMC-SC4	UVES	2001/05/17	1.86	CCD-44	CD#1	600	52411.41268	0.26
SMC-SC4	UVES	2001/05/17	1.81	CCID-20	CD#4	600	52411.42434	0.26
SMC-SC4	UVES	2001/05/17	1.81	CCD-44	CD#1	600	52411.42435	0.26
SMC-SC3	MIKE	2007/11/09	1.43	Lincoln-Labs+SITE ST-002A	echelle	500	54413.03654	0.08
SMC-SC4	MIKE	2007/11/09	1.42	Lincoln-Labs+SITE ST-002A	echelle	500	54413.04421	0.14

**Table 2.** Summary of *FUSE* Observations. Phases refers to the ephemeris given in Table 1.

object	UT-date	UT-start	exptime (s)	mjd-obs	phase
SMC-SC3	2006/10/05	04:05:06	2430	54013.18427083	0.72
SMC-SC4	2006/11/30	11:36:26	2736	54069.49946759	0.27

the column density and assumed  $T_c$ . Most of our analysis is for absorption features. However, for the cases of far-UV C III multiplet, the optical He I, and strong Fe II lines, we fit line profiles with a medium radiating in emission, that is, as if were formed in lines of sight other than those intersecting the star disk.

## 4 RESULTS

### 4.1 Photometry

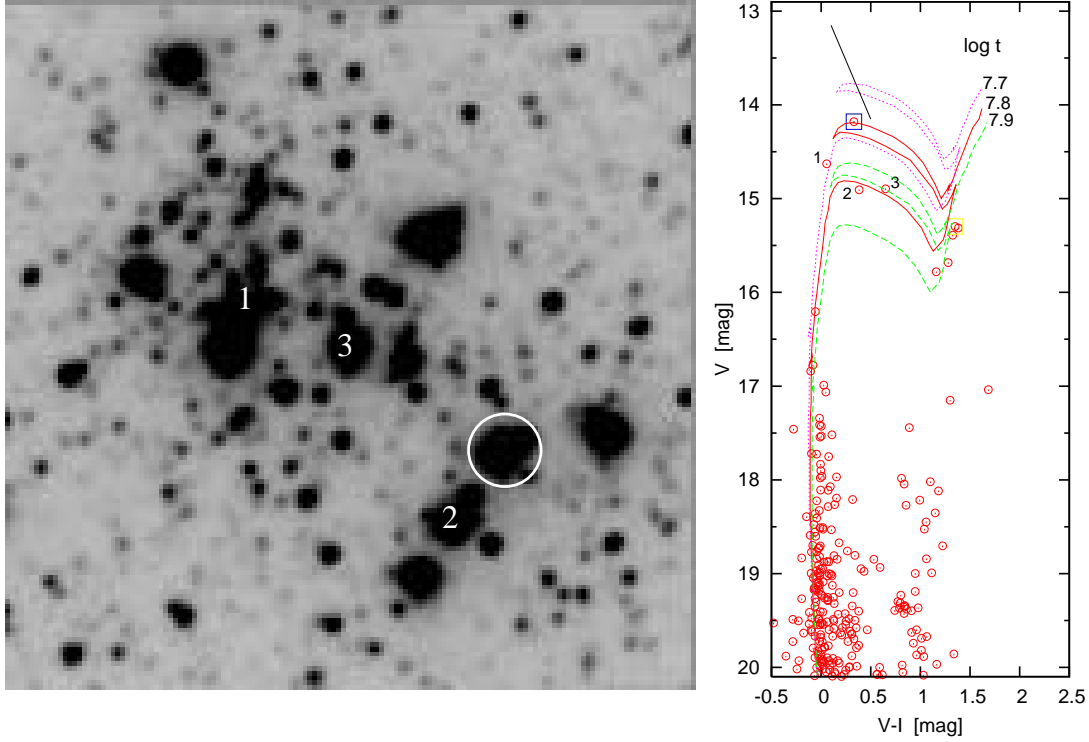
Magnitudes and colors for both program stars are given in Table 3. Their derived colors are consistent with reddened early B or late O type stars, but the reddening cannot be estimated well because most of it occurs in the stars CS disks. For example, in Table 3 a crude estimate based on the  $Q$  reddening-free parameter gives a color excess  $E(B - V) = 0.27$  and  $0.29$  magnitudes for SMC-SC3 and SMC-SC4, based on their assumed intrinsic  $B - V$  colors, “BV0.” An alternate estimate of the influence of reddening can be obtained by using the Exposure Time Calculator (ETC), a tool used by proposers to the Hubble Space Telescope Guest Observer program. It gives consistent count rates for the measured *FUSE* flux at  $1180 \text{ \AA}$  and the  $V$  magnitudes, leading to equivalent  $E(B - V)$  values of  $0.38$  and  $0.48$  magnitudes, respectively. However, because the Hubble ETC tool likewise assumes a normal Galactic reddening curve from the far-UV to optical regimes, whereas the far-UV dimming in our case is most likely due to a complicated array of atomic and molecular line absorptions, we can claim the latter only as estimates useful for comparing fluxes in the visual and far-UV wavelength regimes.

For the purposes of comparing our program stars to B[e] stars, it is useful to know that the observed ( $V - K$ ) colors for our program stars are about +1.0 magnitude (see Table 3). Anticipating results below for the intrinsic ( $V - K$ ) color of a B0 I star, -0.7 (Tokunaga 1999), the IR reddening for our two program objects is about 1.7 magnitudes. Comparing this with the range of 1.2-4 magnitudes for this quantity noted above for the 5 known sgB[e] stars in the SMC, we see that the program stars fall on the low side but still within this range.

In Fig. 1 we show the color-magnitude diagram for SMC-SC3 and for neighboring stars present in their field. We investigated the light curves for the stars labelled 1, 2 and 3 and they are quite constant. The figure also depicts isochrones for the cluster NGC 242 considering the parameters indicated in the figure caption. It is clear that especially those bright objects lie close to the  $\log t = 7.8$  isochrone. The Fig. 1 also depicts the observed position of SMC-SC3. Its true location the HR Diagram should be projected back along the indicated reddening vector.

Deep exposures of sky images surrounding the two program objects reveal no suggestion of nebulosity. However, during our investigation we discovered that SMC-SC3 has a visual companion (the small bump at the NW of SMC-SC3 in Fig. 1) about 1" from SMC-SC3. We analyzed its OGLE light curve as part of this study and discovered that this visual companion is an eclipsing binary with an orbital period of 2.96934 days,  $V = 16.776$ ,  $V - I = -0.083$  and range of variability in  $I$  equal to 0.77 mag. This nearby star is not in the catalog of eclipsing binaries in the *SMC* (Bayne et al. 2002). It is unlikely that this star influences the periodicities found in the OGLE light curve of SMC-SC3.

The O-C diagram for SMC-SC3 using OGLE II and OGLE III data shows that the 15-day cycle is not constant (Fig. 2a). Adding the MACHO light curves (Allsman & Axelrod 2001), we found that the amplitude of the 15-day periodicity is larger in the blue band (Fig. 2b). On the other hand, the O-C diagram for SMC-SC4 (Fig. 3a) suggests that this star undergoes quasi-periodic occultations. In fact, the  $\sim 184$  day minima are irregular (Fig. 3b), of larger amplitude at the blue band and the O-C diagram indicates that the period varies. All these features, along with the presence of additional quasiperiodic variability in time scales of 24 days (M06), prompt a suspicion that the eclipses are due to obscuration of the star by a rotating inhomogeneity in the CS cloud. The inference that at least a dense CS cloud exists around this star is borne out by our spectroscopic analysis below.



**Figure 1.** The left picture is a finding chart of SMC-SC3 centered on the cluster NGC 242 ( $1' \times 1'$  subframe of the reference  $I$ -band image from the OGLE-II survey). North is up and East left. SMC-SC3 is indicated by a circle and three reference stars are labeled. Right panel shows the CMD for the same region. The CMD is based on the OGLE II standard  $VI$  photometry in the SMC (Udalski et al. 1998). Three isochrones are also presented (Bertelli et al. 1994) for stars with metallicity  $Z=0.004$  and ages ( $\log t$ ) labeled in the picture. We adopted these isochrones using  $V - M_v = 19.0$ ,  $E(V - I) = 0.08$  and  $A_v = 2.5 * E(V - I)$ . SMC-SC3 is marked with an open square and the reference stars with circles. The reddening vector is indicated by the upper oblique line.

**Table 3.**  $UBVI$  magnitudes from Zaritsky et al. (2002) and OGLE photometry are given, along with reddening-free  $Q$  (based on OGLE and Zaritsky  $U$  magnitude),  $Q2$  (entirely based on Zaritsky photometry) and  $B - V$  indices (based on the  $Q$  factor) and the color excess according to the Johnson & Morgan (1953) calibration.

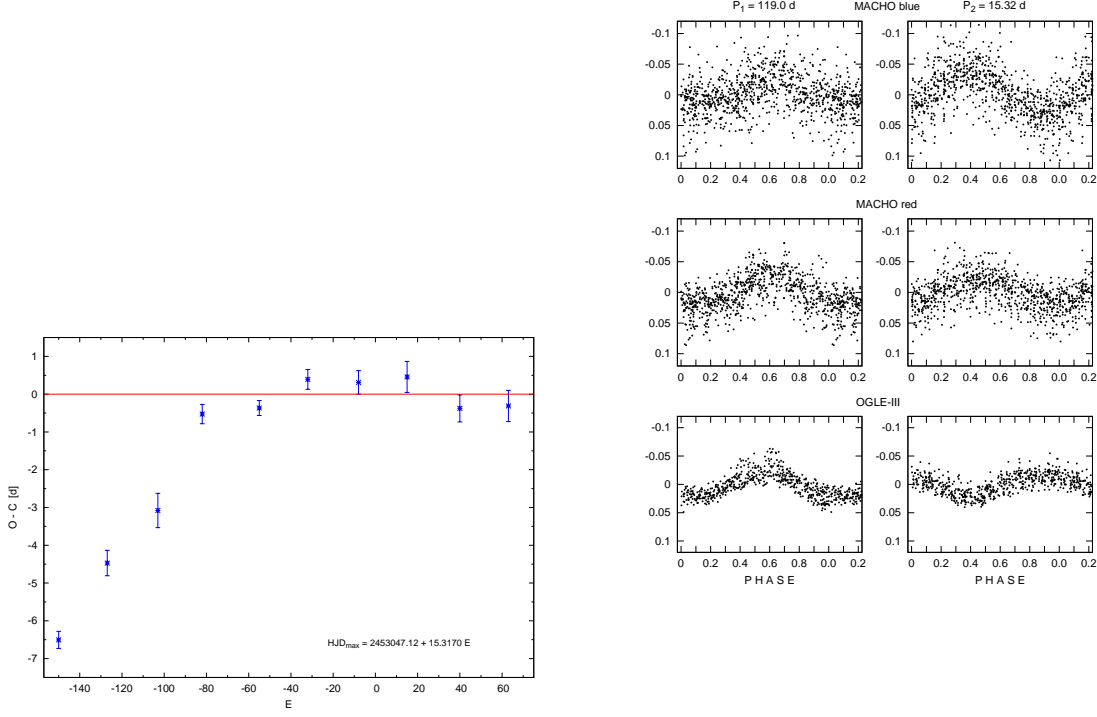
Object	U	B	V	I	V(OGLE)	BV(OGLE)	VI(OGLE)	Q	Q2	BV0	EBV
SMC-SC3	14.262(40)	14.392(33)	14.085(26)	13.729(23)	14.18	0.181	0.331	-0.23	-0.35	-0.09	0.27
SMC-SC4	14.179(89)	14.205(21)	13.945(72)	13.617(86)	14.06	0.206	0.385	-0.24	-0.21	-0.09	0.29

## 4.2 Spectroscopy

### 4.2.1 Optical lines and radial velocities

We have identified many absorption lines in our spectra by correlating their central wavelengths (measured by simple or multiple gaussian fits or simply with the cursor in a high resolution display) with vacuum atomic wavelength lists. For most of these lines we have obtained radial velocity measurements which are summarized in Table 5. We find only small variances among the velocities of the various ions, at least for the primary components of lines formed in those ions prevalent in the circumstellar gas cooler than 10 kK. The average for 178 lines in SMC-SC3 is  $107 \pm 12 \text{ km s}^{-1}$  and for 75 lines in SMC-SC4 is  $105 \pm 9 \text{ km s}^{-1}$  (2007 data). This figure is close to the same for



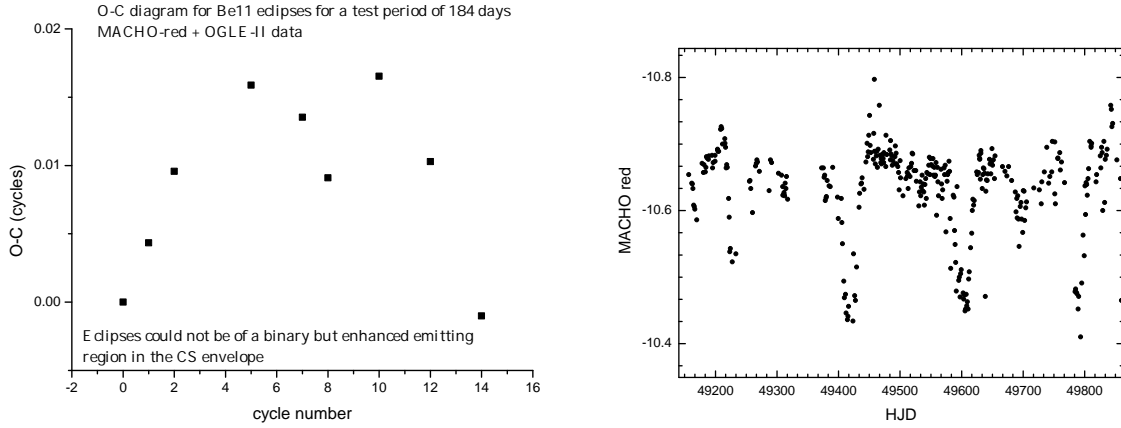


**Figure 2.** Left: O-C diagram for the 15-d periodicity of SMC-SC3. Each point was calculated for one season (number of observations per season is from 60 to 100) and the model fit includes both periods. The primary period  $P_1 = 119$  d has non-sinusoidal shape, therefore its first harmonic was added ( $2 \times f_1$ ) in the final fit. The ephemeris was calculated using the second period ( $P_2 = 15.3170$  d) from the OGLE III data, since for these epochs it seems to be constant. Right: MACHO and OGLE III light-curves of both periods detected in SMC-SC3 are folded with  $HJD_0 = 2450000.0$ . This figure illustrates the  $P_2$  period change and the amplitude difference between bands. Note that  $P_1$  has a non-sinusoidal shape.

**Table 4.** Infrared magnitudes for program stars. Phases refers to ephemeris given in Table 1.

Object	I	J	H	K	JD/Date	phase	Source
SMC-SC3	13.701(9)	13.346(22)	-	12.954(116)	1998-08-12	0.72	DENIS Catalogue
SMC-SC3	13.847(30)	13.472(90)	-	13.050(180)	2450414.6148	0.48	DENIS Consortium
SMC-SC3	13.781(40)	13.560(110)	-	13.134(160)	2451048.7763	0.81	DENIS Consortium
SMC-SC3	-	13.545(42)	13.341(50)	13.275(40)	2451034.7109	0.69	2MASS
SMC-SC4	13.655(30)	13.388(90)	-	13.316(210)	2450418.5524	0.42	DENIS Consortium
SMC-SC4	13.616(30)	13.383(130)	-	13.079(150)	2451039.7991	0.79	DENIS Consortium
SMC-SC4	-	13.403(29)	13.236(34)	13.054(35)	2451034.7134	0.77	2MASS

the 2001 spectra and indicates almost the same radial velocities for the circumstellar regions of both stars. We observe moderately strong  $V$  and  $R$  emission components in the lower members of both the Balmer and Paschen series. The relative strengths of these features decrease to invisibility by  $H_\zeta$ . These lines are flanked by absorption wings, typically stronger in the blue wing, and have a deep central absorption. The central absorption cores are found blueward the centroid of the  $V$  and  $R$  emission peaks typically by a few  $\text{km s}^{-1}$  (Table 6). Remarkably, we found blue absorption components (BACs, discussed later) in most metallic lines of SMC-SC4 with a blue shift with



**Figure 3.** Left: O-C diagram for SMC-SC4. Right: Variability of eclipses in SMC-SC4.

**Table 5.** Summary of heliocentric radial velocities (in km/s) for MIKE spectra. For SMC-SC4 we give the velocity of the red (assumed “main”) component and the velocity of the BACs when available after the semicolon. The number of lines included in the averages is also listed.

Ion	SMC-SC3	SMC-SC4	Ion	SMC-SC3	SMC-SC4	Ion	SMC-SC3	SMC-SC4
CaI	108±12 (2)	- ; 56 (1)	HI	106±3 (28)	105±6 (28) ; -	ScI	112 (1)	- ; 58 (1)
CaII	106±5 (5)	-	MgI	103±6 (3)	104 (1) ; -	ScII	115±14 (2)	-
CrI	81 (1)	-	MgII	115±24 (3)	141 (1) ; -	SiII	127±27 (7)	-
CrII	104±11 (10)	100±10 (3) ; 54±11 (6)	NI	105 (1)	-	SrII	106±13 (2)	-
FeI	110±12 (27)	- ; 49±3 (2)	NaI	109±2 (2)	108±3 (2) ; -	TiI	98±26 (7)	-
FeII	106±3 (41)	104±6 (30) ; 53±5 (21)	OI	104 (1)	-	TiII	105±7 (35)	110±16 (9) ; 51±7 (6)

respect to the primary absorption line components. This shift averaged  $-50 \text{ km s}^{-1}$  in 2001 and  $-58 \text{ km s}^{-1}$  in 2007. The differences between these two epochs while small are probably significant.

**Table 6.** Heliocentric radial velocities (in km/s) for H I emission line components and shift of the central absorption relative to the centroid of the red and violet emission peaks. NP means not present. Note the larger peak separation in higher order lines.

Emission line	star	year	blue-peak	central-abs	red-peak	shift
H $\delta$	SMC-SC3	2007	20	107	172	-2
H $\gamma$	SMC-SC3	2007	31	93	168	-6
H $\beta$	SMC-SC3	2007	32	92	166	-7
H $\alpha$	SMC-SC3	2007	46	91	152	-8
H $\delta$	SMC-SC3	2001	-	-	-	-
H $\gamma$	SMC-SC3	2001	-	-	-	-
H $\beta$	SMC-SC3	2001	24	95	159	-4
H $\alpha$	SMC-SC3	2001	55	93	153	-11
H $\delta$	SMC-SC4	2007	NP	104	NP	-
H $\gamma$	SMC-SC4	2007	NP	106	NP	-
H $\beta$	SMC-SC4	2007	NP	112	181	-
H $\alpha$	SMC-SC4	2007	64	111	165	-4
H $\delta$	SMC-SC4	2001	-	-	-	-
H $\gamma$	SMC-SC4	2001	-	-	-	-
H $\beta$	SMC-SC4	2001	46	105	195	-16
H $\alpha$	SMC-SC4	2001	56	114	170	-1

**Table 7.** Equivalent widths ( $EW$ ), maximum intensity relative to the continuum ( $I/I_c$ ) and full width at half maximum ( $FWHM$ ) for the  $H_\alpha$  emission line in 2001 and 2007.

Object	$EW$ (Å)	$I/I_c$	$FWHM$ (Å)
SMC-SC3	112-104	24.1-22.7	4.39-4.46
SMC-SC4	28-26	6.3-5.7	5.16-5.25

#### 4.2.2 Photospheric lines, $T_{\text{eff}}$ , and FUV radial velocities of SMC-SC3 and SMC-SC4

For SMC-SC3 we estimated a spectral type of O9-B0, based, first, on fitting of the wings of both He I 3821 Å and  $H\beta$  as compared to these wings in O7-B0 Ib-III stars taken from the UVES POP webpages (Bagnulo et al. 2003). The (usually red) wings of the Balmer and Paschen lines were also used to confirm this spectral type and  $T_{\text{eff}}$ , given the implied luminosity class of III. The C III 1176 Å widths/wings suggest a slightly cooler spectral type of 30-32 kK. Based on this, we used 31 kK,  $\log g = 3.5$  from Kurucz models (Kurucz 1993). The precise photospheric temperature does not appear to be important in the modeling of the CS absorptions discussed herein.

It is not clear how many lines in our spectra of SMC-SC4 are photospheric, but they are few in number. The best candidates are the far wings of the Balmer and Paschen lines and the wings of C III 1176 Å (Figs. 4 and 5). From the similarity in the  $V$  magnitude we also take this star to have a luminosity class of about III. The wings of the hydrogen lines are more developed in SMC-SC4, suggesting a slightly later type. However, the C III 1176 Å feature is indistinguishable from the SMC-SC3 line. To split the difference between the implied values of  $T_{\text{eff}}$ , we used a Kurucz model of 29 kK,  $\log g = 3.5$  to model the photospheric fluxes.

Because of the dearth of photospheric lines we have had to rely on the radial velocity differences of the Galactic (LISM) and local (SMC) ISM line components. We then tied the LISM radial velocity to the Sun's so that this ISM velocity difference could be taken as an estimate of the program stars' systemic velocities. ISM components of a number of low excitation ions are plentiful in our *FUSE* spectra, and we were able to measure velocity differences for both stars. Our results for SMC-SC3 and SMC-SC4, respectively, were  $119 \pm 4.9 \text{ km s}^{-1}$  (39 lines) and  $110 \pm 6.1 \text{ km s}^{-1}$  (25 lines), referencing the zeropoint to the measured LISM wavelengths. As a check on these results, we consulted the Tomlinson et al. (2002) compendium of measured SMC ISM lines. The comparable-brightness objects lying closest in the sky to our program stars, AV 14 and AV 15, have RVs of  $124 \text{ km s}^{-1}$  and  $130 \text{ km s}^{-1}$  (with  $\pm 9 \text{ km s}^{-1}$ ), which are in the expected rough agreement. Furthermore, the measurements of the optical lines discussed in section 4.2.1 are consistent with these RV values and a low velocity CS expanding medium in both our 2001 and 2007 data.

### 4.2.3 The circumstellar features in SMC-SC3

#### a. General description:

With the exception of the broad wings of  $H\beta$ , He I 3821 Å, and possibly of the far-UV C III 1176 Å multiplet, none of its optical or near-IR lines are photospheric. Rather, they reflect different kinematic and thermal properties of an extensive circumstellar envelope. The orbit of a dense property may be responsible for the near or strict periodicity with a period of 119 days. The high-level Balmer and Paschen lines can be resolved to H30 and P24, respectively, leading us to estimates of a mean envelope volume density of  $\sim 1 \times 10^{11-12} \text{ cm}^{-3}$ . The first few members of the Balmer line spectrum show strong emission, with  $I_{H\alpha} = 24I_c$ , and  $V/R = 0.9$  (Table 7 and Fig. 6). We have no direct information on the degree of flattening of this disk structure, but the separated  $V/R$   $H_\alpha$  components suggest a quasi-Keplerian rotation of this structure. We say “quasi”-Keplerian because of the likely very slow outflow of the gas from the star discussed below. Hereinafter, we will refer to a slow wind and quasi-Keplerian disk interchangeably.

The optical spectrum of SMC-SC3 exhibits only various permitted lines formed at “hot,” “warm,” and “cool” temperatures. These lines are mainly in absorption, but a few Fe II lines exhibiting emission wing components will be highlighted below. The high excitation lines of He I, 5876 Å and 7865 Å, are present weakly in emission. Their profiles are narrow and they can be fit with CIRCUS models having (“hot”) temperature of 15–25 kK (probably closer to the upper limit) with column densities of  $5\text{--}10 \times 10^{22} \text{ cm}^{-2}$ . The principal metallic line features are Fe II and Si II absorptions, and these are formed at “warm” temperatures of 6–9 kK (Fig. 7). We suspect also that the excited O I 7771–5 Å triplet ( $\chi = 9 \text{ eV}$ ) is formed in the same warm region as the strong Fe II lines. Both groups of lines have turbulence-broadened wings and are formed optimally in a warm environment. The resonance doublet of Na I and K I doublets are both formed at “cool” ( $\leq 6 \text{ kK}$ ) temperatures. Although the presence of these lines give the red/near-IR spectrum the appearance of an F–G supergiant photosphere (M06), close inspection at high resolution demonstrates that the Na D lines have multiple components and a shaded blue-wing, suggesting a highly differentiated velocity structure. In our *FUSE* spectra, we are able to make out both the Galactic and SMC ISM components; the latter appear to show only one significant component toward either of our program stars. The radial velocities (RV) of the Na I lines range from those exhibited by the Balmer, Fe, and Si lines to the largest measured, possibly indicating an outflow with a larger velocity gradient than found in the component forming the latter group of lines. Fig 4 shows that in the case of

SMC-SC4 a portion of the line (blue wing) is formed in a region flowing outward faster than the flow of the mean disk.

One interesting aspect of the strongest metallic lines of SMC-SC3 (but not SMC-SC4) is that in addition to their sharp cores they also have strong wings (Fig. 8a). However, these wings are neither extensively tapered nor symmetric, i.e., the profiles do not resemble Lorentzians. Also, because some of these wings, notably those of Fe II 5018 Å, 5169 Å, and 5197 Å are in emission, and because the excitation potentials of the lines can be low, we strongly doubt that these line components are photospheric. In the case of Fig. 8a we obtained similar fits with microturbulence ( $\approx 50 \text{ km s}^{-1}$ ) or macroturbulences ( $\approx 60 \text{ km s}^{-1}$ ) and for column densities of at least twice those (i.e.,  $\approx 2 \times 10^{23} \text{ cm}^{-2}$ ) needed for the inner region of these lines.

*b. Fitting equivalent widths with CIRCUS:*

Our modeling proceeded in most cases with a single microturbulence value ( $\xi = 5\text{--}10 \text{ km s}^{-1}$ ) and one temperature. The sample of fitted lines shown below is a strategically chosen subset of a larger group of fitted lines. Except for He I lines and Na I and K I doublets, we are able to model all the UVES lines of both SMC-SC3 and SMC-SC4 with  $T_c$  values of either 8 kK or 5 kK. In some short stretches of the spectrum two different temperatures are necessary (Fig. 7), meaning that actually the temperatures vary smoothly with position from the star. We have also been able to fit the emissions of Fe II 5018 Å (Fig. 8b) using an LTE representation (emission + absorption) components. Other lines are represented by absorption only, i.e. the source function in the line is zero. Excepting the hydrogen lines as one proceeds to less excited species, higher and higher column densities are necessary to fit the spectra, e.g.  $1\text{--}3 \times 10^{22}$  for He I, and about  $1 \times 10^{23} \text{ cm}^{-2}$  for the 5 kK and 8 kK gas components. In contrast, the optical depth of the high level Balmer lines, which are formed in gas with all these temperatures, suggests a total hydrogen-absorbing column density of about  $10^{24} \text{ cm}^{-2}$  and a volumetric density of  $10^{11\text{--}12} \text{ cm}^3$ .

We have attempted to fit the  $H_\alpha$  emission strength. Using our LTE models with  $T_c = 9 \text{ kK}$  and  $\xi = 10 \text{ km/s}$ , we found an implied total area of  $\sim 10\,000$  stellar areas, such that the extent of the disk is roughly  $\sim 100 R_\star$ . This is roughly consistent within the errors with the  $V, R$  velocity separations indicated in Fig. 6 and also with the disk emission area of 2 500 areas we derive from the Fe II 5018 Å emission (Fig. 8b). However, we reiterate that these fittings were done with LTE models, the numerical value we derived especially for  $H_\alpha$  should be taken at most to an order of magnitude.

Additional evidence of a warm emitting gas seen beyond-the-limb sight lines is furnished by the weakened C III 1176 Å multiplet, which requires hot gas to mimic a  $\approx 25\%$  dilution of the

line by an additional radiation field. We require a  $T_e = 25$  kK component having about 5 emitting stellar areas to accomplish this (Fig. 5a). In principle, these emission areas can be used to compute hydrogenic Stromgren spheres. We estimate that the radius of this sphere is that of a O9.5-B0 star, consistent with our estimate in Section 4.2.1 from the 1176 Å and optical H I and He I lines. We also point out that the 25% dilution for C III 1176 Å, suggesting a substantial far-UV continuum emission component, from a volume *around* the star, is greater than the several percent dilution we observe in the D lines. This suggests that flux contribution in optical wavelength is smaller, and this is generally consistent with the inference that the far-UV continuum emission comes from a region cooler than the photosphere.

#### 4.2.4 *The circumstellar features in SMC-SC4*

Nearly everything stated about SMC-SC3 in its introduction is also true of SMC-SC4. Once again it was difficult to find photospheric absorption lines; the SMC-SC4 spectral type may be O9-B0 or B0, according to its stronger H-line wings. The high level Balmer line limits are H29 and P23 (compared to H30 and P24 for SMC-SC3), so its mean volume density and total column density is close to than the disk densities for SMC-SC3. The  $H_\alpha$  emission is 4 times weaker than for SMC-SC4 ( $I_{H_\alpha} = 6I_c$ ), and  $V/R \sim 1$  (Fig. 6). Assuming a similar excitation temperature and a similar electron density from the visibility of the high level Balmer lines, the gas component of the SMC-SC4 disk is about half as extensive as the SMC-SC3 disk.

Multiple temperature fits were constructed using CIRCUS for several features in the UVES spectrum, just as with for SMC-SC3. The gas in SMC-SC4's disk likewise shows layered temperatures. Again as with SMC-SC3, there is evidence of line or continuum emission close to the star, and there is a very faint emission in the He I 5015 Å line. The 5876 Å and 7065 Å lines consist of both weak emission and absorption components. Also, our remarks for the dilution of the SMC-SC3 C III 1176 Å are equally valid for the fitting of this feature in the SMC-SC4 spectrum - see Fig. 5b. As before, in order to fit the C III 1176 Å feature we had to introduce a hot emitting region of about 5 stellar areas to the photospheric flux. For both stars it appear that this flux is consistent with the appearance of the He I lines in the optical spectrum.

In the SMC-SC4 spectrum the observed lines are formed exclusively in absorption and arise from a diversity of excitation states. These include the hydrogen lines, the high excitation O I 7771-5 Å triplet (9 eV), the many lines of Fe II and Si II, and finally the Na D and K I resonance doublets. Our models show that the K I line is formed at a temperature of 5 kK or less. A comparative

weakness of the KI and OI lines in the SMC-SC4 spectrum is consistent with the only moderate emission in  $H\alpha$ .

The primary difference that the SMC-SC4 spectrum exhibits with respect to SMC-SC3 is the presence of one or two Discrete Blue Absorption Components in almost all the metallic lines. We call these features "BACs." These are blueshifted by 50-58 km/s relative to their "main" absorption members. As an example, the strongest Fe II lines (Fig. 9a) are accompanied by two blue BAC features each separated by  $-30 \text{ km s}^{-1}$ . The middle absorption component of these is absent in any other lines in our spectra. An important difference between the  $5018 \text{ \AA}$  (2.9 eV) and its slightly stronger multiplet members  $4923 \text{ \AA}$  and  $5169 \text{ \AA}$  is that the  $5018 \text{ \AA}$  line exhibits a broad absorption wing. The red wings of the other two lines reach the continuum abruptly and hint at the presence of red emission. This trend continues as one goes to less strong Fe II lines, such as  $5276 \text{ \AA}$  and especially  $5272 \text{ \AA}$  (see Fig. 7; lower spectrum). The latter are somewhat filled in by emission, according to the pure-absorption models that fit most of our other weaker Fe II line absorptions well. Yet weaker but still fairly strong lines arise from the same excitation potential; Fig. 10a shows this emission for  $5169 \text{ \AA}$  and also in the red wing of the Mg I  $5172 \text{ \AA}$  line. Tracing these characteristics altogether, from the intermediate-strength Fe II lines to the lines of the more abundant ions Mg I and Si II, there is a trend that the lines with the highest optical depth exhibit the greatest tendency for the "main" red component to be filled in by emission. This is the typical signature of P Cygni emission in an outflow with only a small expansion velocity. The emission originates from scattering of line flux from a large annular region in the sky plane around the star (though primarily along the disk axis). This conclusion is required by the required coverage factor of many stellar-areas to model the metallic line emissions in our CIRCUS models (see Figs. 8b, 9b, 10a). These models demonstrate that the emission is too large to be caused by gas heating along lines of sight directly to the star.

Although the BACs are a highlight of SMC-SC4 optical spectrum, they are not unique to this star. In a little noted paper, Heydari-Meydari (1990) reported that the metallic absorption lines of the sgB[e] star N82 for the most part consist of double components, the dominant member of which is blueshifted by about  $-46 \text{ km s}^{-1}$ . In addition, we notice a faint vestige of BACs at the same velocity also seem to be present in the Mg II  $4128 \text{ \AA}$ ,  $4132 \text{ \AA}$  doublet in the SMC-SC3 spectrum - see Fig. 10b. These similarities prompt the speculation that our program stars are part of a larger group - we call them "bgBe stars." Such stars must have extensive and kinematically complicated (but slowly expanding) disks in the central plane in which either high turbulence or colliding wind

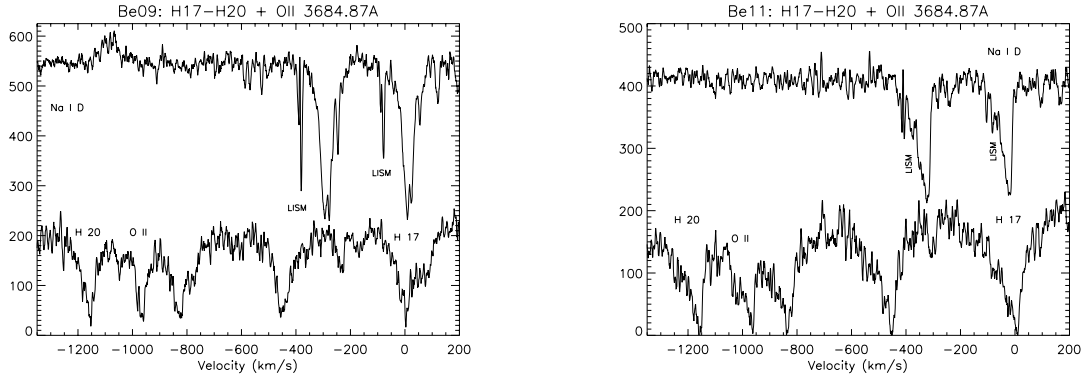
components are common. If so, they may form a morphological if not evolutionary bridge between sgB[e] and classical Be stars.

#### 4.2.5 *Comparison of the UVES and MIKE optical spectra*

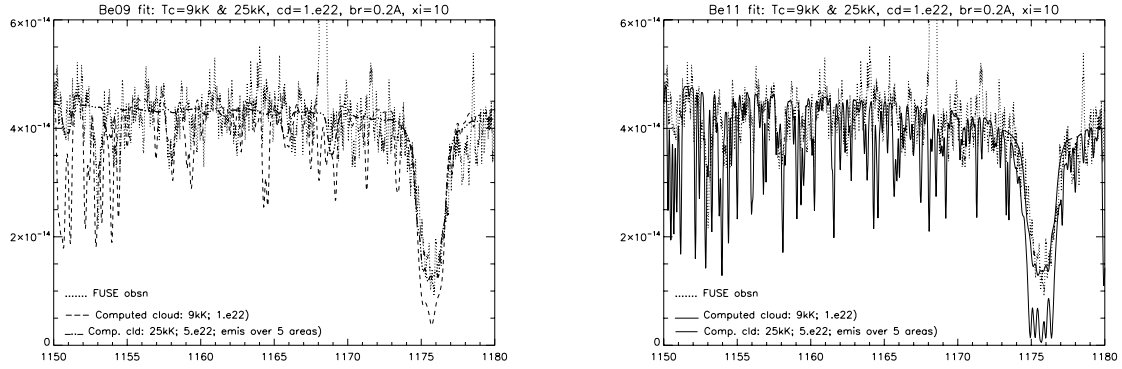
As noted in §4.2.1, the measured radial velocities are practically the same from our high resolution UVES and MIKE spectra obtained in 2001 and 2007. The roughly constant wavelength spacing between the absorption components in Na D (one is the Galactic ISM component) suggests that there is little or no change in RV in the reference frame of the outer regions of the CS disk between our two observing epochs. One of the conclusions from the absence of clear RV changes is that short-period binarity is unlikely. Second, we see almost no difference in the high level hydrogen or metallic line strengths of SMC-SC3 between the 2001 and 2007 spectra. For SMC-SC4 there are only subtle differences in the line profiles. Among these are: (1) the  $H\alpha$  emission is slightly weaker; the  $V/R$  ratio, now  $>1$ , is reversed, but still is close to one, and (2) the multiple components in the strongest Fe II and Na D lines are sharper in the 2007 spectra. Thus, while the details of the wind flow are slightly different, the general slow outflow characteristics are the same. For SMC-SC4 the new spectra show several blue Fe II lines that were not so clear before, and the generally sharper BAC components bring out the emission. Two of these are Fe II 4585 Å and 4632 Å; the “main” (red) component shows very clear P Cygni-like structure, which we could barely discern in the 2001 spectra.

The 2007 spectra also cover the blue region of the Ca II H/K lines, which were not included in the 2001 UVES observations. This doublet exhibits developed wings. While the line cores do not reach the zero flux level, like the D lines they are deep enough to suggest that a putative cooler companion could not contribute much flux in the blue spectral region. As with the Na and K resonance lines, these profiles would account from the previous F spectral type for SMC-SC3 based on low resolution spectra (M06). We do not believe these features are photospheric, but rather that most of the column density of the disk is concentrated far from the star where  $T_e \leq 8$  kK. For one thing, the CaII K line core of SMC-SC4 exhibits a double-lobed structure, suggestive of the BACs in the very lines that flank it. This and the fact that narrow cores drop down to low fluxes suggests that at least these parts of the lines are CS in origin. The line wings are far too strong to be formed in the photosphere of a  $\sim$ B0-type star.

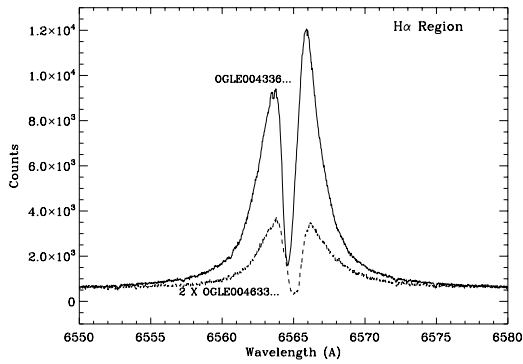




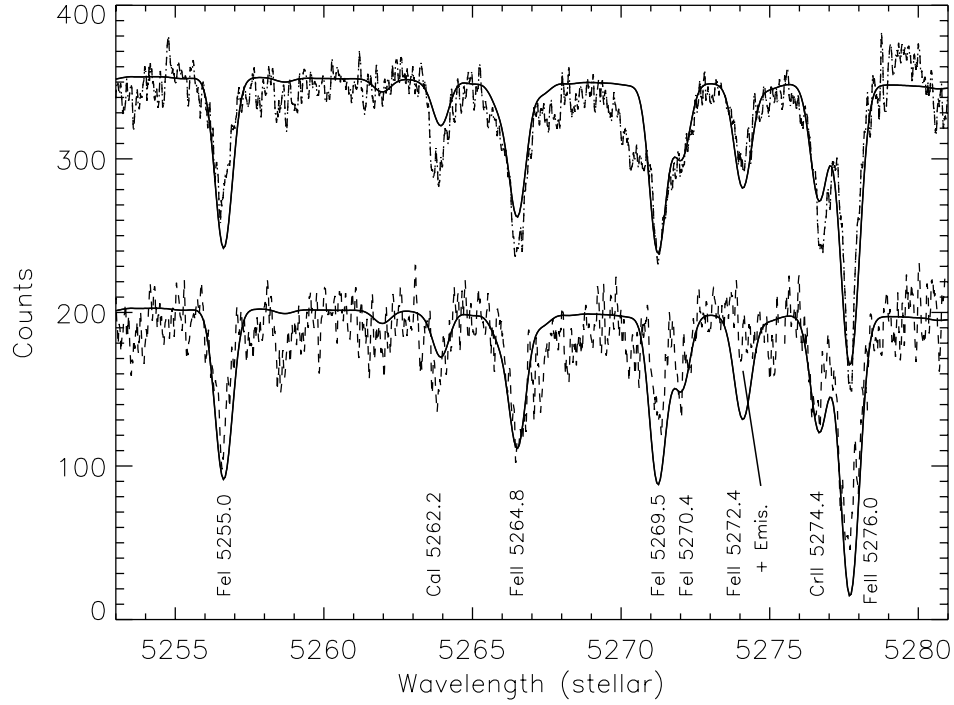
**Figure 4.** A comparison of the Na I D doublet and the high level Balmer lines in our UVES spectra for SMC-SC3 (left panel) and SMC-SC4 (right panel). The zero points of the velocity system are referred to the rest frames of the D2 (5896 Å) and H17 lines.



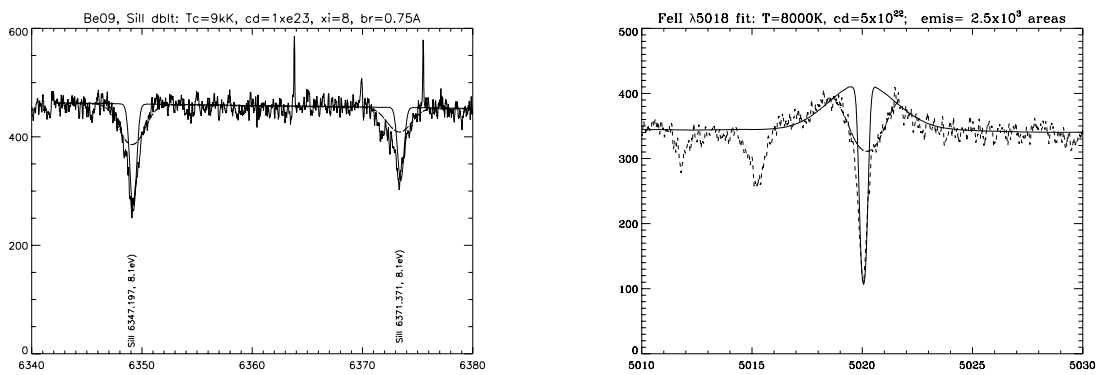
**Figure 5.** Fit of C III 1176 Å for SMC-SC3 (left panel) and SMC-SC4 (right panel). The dashed lines are FUSE observations, while the solid and dotted lines are fits without and with the emitting line dilution discussed in the text. Annotations indicate the model parameters.



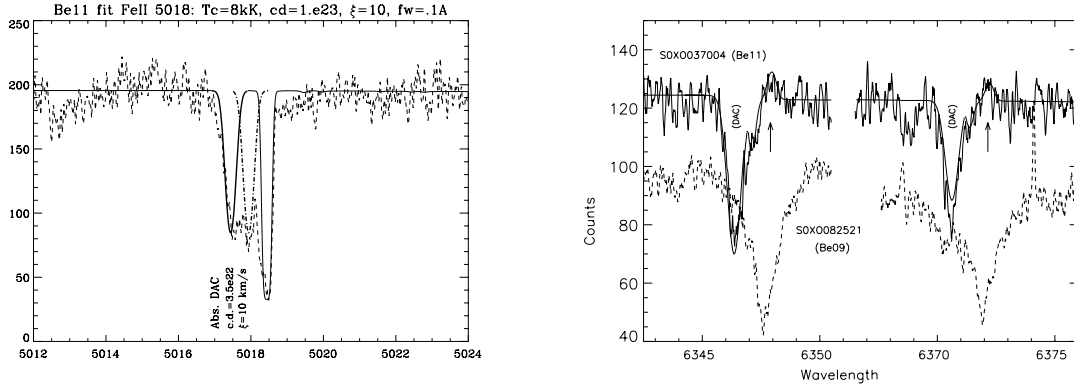
**Figure 6.** The UVES spectra depicting the Hα profile for both the program stars.



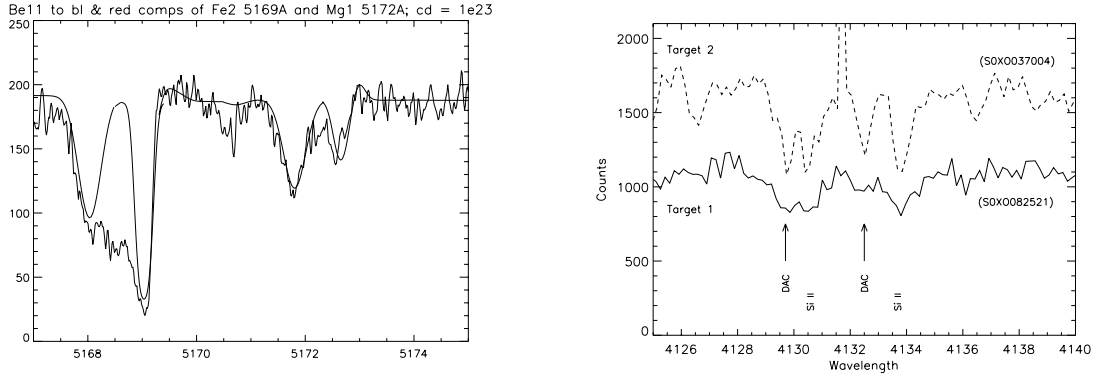
**Figure 7.** The two temperature fit of yellow Fe-like lines for SMC-SC3 (upper) and SMC-SC4 (lower). In both cases temperatures of 8 kK and 5 kK were used and the warm column density was  $1 \times 10^{23} \text{ cm}^{-2}$ . For the respective stars, the columns for the cool component were  $1.5 \times 10^{22} \text{ cm}^{-2}$  and  $0.5 \times 10^{22} \text{ cm}^{-2}$ .



**Figure 8.** (a) A fit for the core and wings of Si II the 6347 Å and 6371 Å doublet for SMC-SC3, using a temperature of 8 kK and two separate turbulencies of  $10 \text{ km s}^{-1}$  and  $50 \text{ km s}^{-1}$  and column density fitting models. (b) A fit of the Fe II 5018 Å line for SMC-SC3. This profile was fit by two independent models, one with a temperature of 8 kK and a column density of  $5 \times 10^{22} \text{ cm}^{-2}$  and a low microturbulence of  $10 \text{ km s}^{-1}$ . The second component was fit to the emitting wings with the same CS temperature, only with a medium extended over 2 500 emitting stellar areas and a turbulence of  $50 \text{ km s}^{-1}$ .



**Figure 9.** (a) The Fe II 5018 Å line of SMC-SC4, exhibiting *two* Discrete Blue Absorption Components (“BACs”). (b) A fit to the Si II 6347 Å and 6371 Å doublet (solid line), emphasizing the BACs and the filled in main components for the SMC-SC4. The observed spectrum (only) is shown for SMC-SC3, in order to guide the eye to the filled in emission in the SMC-SC4 spectrum. For both spectra the 6371 Å line has been displaced for convenient reference.



**Figure 10.** (a) The region around the Fe II 5169 Å and Mg I 5172 Å lines in the spectrum of SMC-SC4. The observations were fit to a two absorption model, with the BACs each being fit with a 8 kK gas with a column of  $1 \times 10^{23} \text{ cm}^{-2}$  and blue shifted by  $-35 \text{ km}^{-1}$ ; the red component was fit with a column of  $3 \times 10^{23} \text{ cm}^{-2}$ . The Mg I emission component was produced with 10 stellar areas having this same temperature; the “main” (red) component of the Fe II line was unaffected by this emitting area. (b) A comparison of the profiles of the 8 eV Si II 4128-4132 Å doublet for SMC-SC4 (dashed) and SMC-SC3. Discrete blue absorption components, while clearly seen in the SMC-SC4 spectrum, are barely visible in SMC-SC3.

## 5 DISCUSSION

In order to interpret the variability and spectral characteristics observed in our targets, in principle we can invoke mass loss/exchange in a binary system with two nearly equal mass components. However, we have rejected this hypothesis because of the unmeasurable changes in RV, small departures from strictly periodic variability in the light curve, and the absence of a secondary component in the hydrogen and resonance line spectra. Rather, to date the evidence supports the view that these objects are effectively single stars surrounded by a slowly expanding disk which is fed by a moderate velocity wind close to the star.

The chances of our initially selecting two stars with unexpectedly anomalous spectra out of a group of eight otherwise normal B stars are very low. Therefore, we suspect that the bgBe stars are comparatively numerous in the SMC fields S02 surveyed, perhaps accounting for at least 10% of all the Type 3 B variables down to  $V = 14$ . Even so, somehow these objects certainly represent a short-lived stage in the evolution of OB type stars in at least the SMC.

The most striking spectroscopic characteristic of these objects is their confined thick disks, which seem to be tied to winds. Although we do not yet know whether, like many B[e] stars, these CS systems have a hybrid nature, it is tempting from our observations to speculate that the wind has both a slow and moderate or fast velocity component along the same sight lines. In this context, Madura et al. (2007) have discussed B[e] wind models in which a fast wind solution abruptly develops a “kink,” quickly transitioning to a slow component. The kink solution is due in part to the rapid rotation of the star. Rapid rotation could have been initiated either after pre-main sequence evolution (an oft-advanced picture for classical Be stars), from spin-ups via intra-binary mass transfer from a now evolved companion (like  $\phi$  Per), or from spin-up during a blue loop phase of late (single-star) stellar evolution, as sometimes posited for sgB[e] variables (Langer & Heger 1998). The evidence does not rule out any of the three scenarios, although the case for mass transfer in a massive close binary (i.e., with an orbital radius less than a few A.U.) so far seems the weakest.

Regardless of how the bgBe stars evolve to the early B (roughly) class II-III region of the HR Diagram, fundamental questions remain concerning a clearly complicated geometrical and kinematical structure. In global terms, the disk must be an equatorially confined disk with a possible, nonaxisymmetric component, which undergoes Keplerian rotation and a small outward outflow component near this plane. In this last sense, the “disk” seems to be closely tied to a slow wind, probably even slower in velocity than the slow equatorial winds of sgB[e] stars. In this one sense, the disk has intermediate kinematic properties between the Keplerian disks of Be stars and slowly expanding disk/winds of sgB[e] variables.

We may summarize the evidence that the structure around the bgBe stars in this study are disks from the following observations:

- The double-peaked  $V$ ,  $R$  emissions of the peak in  $H_\alpha$  and other lower members of the lower Balmer sequence. This is a key signature of Keplerian rotation in equatorially confined disks, as seen by an observer viewing the system at an intermediate or edge-on angle.

- The reversal of the  $V$ ,  $R$  emissions on a timescale of a few years is likewise associated with Be-like disks.
- The half-power emission peaks of the lines are broader as one moves up Balmer lines from  $H_\alpha$ . This too is the hallmark of Keplerian rotation in Be stars. The larger emission widths result from a lower opacity in the high level lines, thereby sampling a larger equatorial rate closer to the star.
- The presence of emission centered nearly in the wavelength frame of the primary CS absorptions is consistent with Keplerian motion.
- The nearly periodic variations of the light curve strongly suggest recurrent occultations by a structure in the plane.

At the same time, there is evidence that the disk is actually part of a very slow equatorial wind or outflow:

- (i) strong lines such as the wings of the Balmer and Paschen lines, and in addition the Na D lines, exhibit a slight strengthening of the blue wing, which is consistent with an accelerating flow, at least in some sight lines to the star.
- (ii) the cores of the  $H_\alpha$  are shifted to the blue by  $7\text{--}8 \text{ km s}^{-1}$  relative to  $H_\delta$  (Table 6). This puts a strong lower limit to an outflow velocity to the more superficial disk formation sites for  $H_\alpha$  relative to the other lines.
- (iii) In the metallic lines of SMC-SC4, the redshifted emission in the Si II 6347 Å and 6371 Å doublet, some strong Fe II and Mg I lines demonstrates a small blueshift in the “main” absorption component.

In fact, the description of these CS structures are much more complicated than merely of a slowly outflowing axisymmetric disk. Most of SMC-SC4’s spectral lines exhibit one or even two “BACs,” which beg an interpretation of collisions of a comparatively rapid outflowing gas with a more leisurely expanding disk. Indeed, the radial velocities of the BAC components are similar to those of the He I lines, suggesting this component accelerates freely from the star’s equatorial regions over a short distance (probably  $\leq R_*$ ) before encountering the disk. We speculate this outflow maintains the disk mass as it expands from the star. From Fig. 10b, it appears that BACs are present in the SMC-SC3 spectrum too. Their weaker appearance could be caused by a number of factors, among them simply a less massive flow. However, we suspect the primary factor is that the inner flow is less visible if our viewing angle to this star is more edge-on and we cannot see the inner disk interactions as clearly. This would be in agreement with the smaller  $H_\alpha$  emission,

which is a function of projected area, the larger  $E(B - V)$ , and also the similar IR re-emission (from optically thin gas and/or warm dust) with respect to SMC-SC3.

The broad symmetrical emission or absorption wings in the spectral lines of SMC-SC3 require a separate description - indeed one that cannot be said to be unique because there are many ways of generating turbulence. However, one can gain a start in understanding this by noting that a turbulence of at least  $50 \text{ km s}^{-1}$  hints at a source with a considerably higher kinetic energy. The most plausible source is of a high-velocity wind, which abrades the central disk plane as it flows across it. This explanation would likewise explain symmetrical emission due to scattered flux from gas from beyond the stars' limbs. This explanation carries the prediction that a high-velocity wind is present. In this event, tapered blue wings should be visible in the wind-sensitive resonance lines in the ultraviolet. We would further predict that the strengthening of these wings would be slight because lines of sight only intersecting the most visible "upper" limb of the star would sample the high latitude wind.

This latter point brings up the important point that in the envisaged disk geometry, including the Kraus & Lamers opening disks, any observer at equatorial or intermediate viewing angles can expect, through different lines of sight, can expect to sample contributions from strata having different ionizations and velocities. In particular, sight lines intersecting the star's visible pole and equator will tend to run along streams having high and low velocities (and ionizations), respectively. This may account for the variety of components along the Na D and Balmer line profiles that are unlikely be caused by local ISM absorption, particularly for SMC-SC3 (see Fig. 4a). This might also well explain why the strongest broadenings are seen in metallic lines arising from intermediate and high excitations, such as the Si II 6347, 6371 Å doublet and the infrared O I triplet. In summary, the wind/disk systems are difficult to reconcile with simple pictures of either: (1) line forming temperatures decreasing radially outward, or (2) an opening disk, as computed by Kraus & Lamers (2003), with ionization contours streaming radially outward. The evidence supports a picture with components of both these geometries. However, in our opinion the second picture probably is most consistent with the correlation of broadening of single absorption components with excitation potential.

In addition to the complex geometrical and kinematical description, the spatial distribution of the disks of SMC-SC3 and SMC-SC4 offers surprises with respect to the classical Be and the sgB[e] groups. Consider first that forbidden emission lines are a defining attribute of B[e] and especially sgB[e] stars, and yet they are unobserved in these stars. This suggests, despite their

large column density of some  $10^{24} \text{ cm}^{-2}$ , and a likely typical density of  $10^{11-12} \text{ cm}^{-3}$ ,<sup>1</sup> that the disk does not extend to the lower densities ( $\leq 10^{8-9} \text{ cm}^{-3}$ ), that favor forbidden line formation. Consider further the relatively modest infrared excess for these stars of  $\sim 1.7$  magnitudes. This is relatively modest by standards of B[e] stars, although it still falls within the sgB[e] distribution for these excesses.

In all, the disks of the bgBe's are as thick and extensive in radius, enough to be visible in  $H_\alpha$  out to 10's of or even 100 stellar radii. However, the evidence from the absence of [Fe] emission and only moderate IR emission suggests that the disk extents are limited and perhaps suddenly truncated, such that they do not show these expected additional traits. One wonders what mechanism could truncate an otherwise continuing gentle fall off in disk density with distance. As speculation, one possibility is a truncation occurs at the Lagrangian point in a widely spaced binary system, particularly if the putative companion has a low mass. In this case, assuming a disk of extent  $100R_*$  (and thus an orbital radius of  $\approx 5 \text{ A.U.}$ ), a circular orbit viewed even edge-on would imply a radial velocity semi-amplitude of only a few  $\text{km s}^{-1}$ . Thus, a small RV variation in a hypothetically wide spaced system could well be undetectable for a small phase difference of  $\leq 0.2$  cycles.

An even more puzzling attribute of these disks is the modulation of starlight as a large condensation occulting the star once per orbit. This hypothesis presents itself largely through the exclusion of eclipsing binarity, which is untenable for several reasons, the improbability of observing 2 out of 2 widely spaced systems in eclipse being among them.

## 6 CONCLUSIONS

In this paper we have investigated two photometrically variable SMC blue stars, viz. SMC-SC3 and SMC-SC4. These stars show rather exotic properties, such as CS absorption/emission lines, continuum reddening, an almost complete absence of photospheric lines, the presence of blue discrete absorption components (BACs) mostly in metallic lines, *and* the absence of forbidden emission lines. We modeled FUV and high resolution optical lines with SYNSPEC and CIRCUS spectral synthesis codes finding that the spectra can be interpreted in terms of an optically thick slowly expanding and temperature-stratified wind/disk star surrounding both stars. We interpreted discrete blue absorption components ("BACs") as evidence of a velocity discontinuity in the outward flow of matter from the star, or more precisely as evidence for weak shocks formed at the interface

<sup>1</sup> This inference comes from a modeling of the slow decrement of high-level Balmer absorption lines. A high  $N_e$  is needed to permit  $\tau_{line}$  to attain  $\approx 1$  and thus be visible.

between a freely accelerating zone close to the star and a very slowly expanding, flattened disk just beyond it. We take this outer disk to be a relatively dense quasi-Keplerian structure that is the source of  $H\alpha$  emission and the rich metallic line spectrum. We note a key feature, without being able to resolve why, and probably integral to their discovery, that the disks may not be axisymmetric. Nonaxisymmetric density bulges are reminiscent of the periodic migration of one armed density waves, which are excited in the Be disks of many classical Be stars (Okazaki 1991). The appearances of these disk features manifest themselves as periodic oscillations of the ratio  $V/R$  in  $H\alpha$  emission features in the Be stars. In light of the reversal of this ratio between 2001 and 2007 for one of our program objects, one might suspect that the ratios oscillate over time. It is probably premature yet to suggest that this or other alternative disk instability is responsible for the almost periodic light curves until one can associate the light curve variations more closely with disk properties. Nonetheless, it is clear that this association could be accomplished by monitoring the  $V/R$  ratio in  $H\alpha$  in these stars for the predicted variations over the next several years.

Although these objects are similar in some respects to sgB[e] stars, the program objects are unique kinds of Be stars by being less luminous than them and by displaying no forbidden emission lines in their spectra. Additionally, they have disks that are optically thick to many lines. They are also likely to have inhomogeneities which cause nearly periodic long variations in optical brightness. We speculate that these two objects are prototypes of a new type of variable - we have named them bgBe stars - with luminosities midway between sgB[e] and Be stars. Although the bgBe stars are probably not close binary systems, their membership in wide binaries with periods of a few years or longer, cannot be ruled out. Wide binarity may even be favored to explain the absence of forbidden lines.

To shed light on these new bgBe stars, optical spectroscopy is needed on other candidate objects discovered in our surveys of the Clouds. On the basis of extant lower quality spectra, we find at least three other stars in the LMC with properties similar to our two prototype objects. These are OGLE05155332-6925581, OGLE05141821-6912350, and OGLE00552027-7237101. These spectra display moderate to strong  $H\alpha$  emission profiles, high level Balmer absorption lines and variable (possibly regular) light curves. Although the resolution of these moderate-dispersion spectra is insufficient to see faint emissions, none of the spectra show strong forbidden emission lines of Fe II. The spectrum of the first of these is particularly interesting in that it shows BACs, and yet is a Doubly Periodic Variable (Mennickent et al. 2003, Mennickent et al. 2008). Because this object does not have a noticeable IR excess, its membership in a close binary could be important. Follow up observations of these and similar objects are ongoing and will help resolve such ques-



tions as the general prevalence of the bgBe class, the dependence of their properties on metallicity and, for those members with thinner disks, their rotational velocities. Similarly, the observation of UV resonance lines of these objects, so far lacking in these objects, will elucidate the geometrical structure of their winds and perhaps allow the discovery of a high-velocity component.

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